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An Extraterrestrial Influence During the Current Glacial-interglacial

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SUMMARY

Evidence is presented for a category of inner Solar System fragmentation events involving substantially devolatilized cometary bodies which not only give rise to dust singularities responsible for tails, antitails and trails but also provide the bulk of the fragile meteoroidal material reaching the Earth. The most prominent of these events are apparently associated with a swarm of such bodies that moves within the 7:2 Jovian mean motion resonance. Assuming the material released by these events perturbs the atmospheres of Sun and Earth attention is drawn to modulations of the climate during the late Pleistocene-Holocene (i.e. since ~20000 BP) which are in accordance with the growth pattern and cosmogenic signature of the bristlecone pine and appear to be due to the swarm and its source. It follows that the solar-terrestrial relationship may be largely sustained by dust erosion events. To facilitate further astronomical study, we tabulated forthcoming encounters with the swarm and give a short term orbit for the putative source, emphasizing that in the longer term the orbit is essentially chaotic and not reliably predicted. We indicate the likely character of the source in the past and consider also the future celestial hazard to civilization.

1 THEORETICAL PERSPECTIVE

The basic perception of this paper is that of a massive meteoroidal source which experiences intermittent disintegration events of variable intensity and gives rise to the observed helion/antihelion circulation of material in sub-Jovian space. The most prominent of these events result in 'dust singularities' and fluxes of kilometres to metres-sized bodies ostensibly eroding at up to about 10 cm yr^{-1}. The circulation is of disintegration products less than a few kilometres in size therefore whose orbits are not fully dispersed in ecliptic longitude but whose contents nevertheless are sufficiently eroded to be an appreciable cause of the radially stationary and outflowing components of zodiacal dust. It follows that the source structure is probably heterogeneous on kilometre/subkilometre scales commensurate with the size of the meteoroidal bodies produced, depending on the departures from physical homogeneity (pressure, temperature) that arise during the formation of large comets generally. Thus the composition of the source is believed to be essentially porous-chondritic (asteroidal), reflecting an open structure which is welded or glued together by a carbonaceous (organic) component and variously impregnated with frozen (cometary) volatiles which failed to escape during condensation. In other words, the meteoroidal source has the characteristic of the remnant core of a comet of modestly large dimensions (100 km, say) which also experienced a degree of primordial differentiation. To the extent that this object is, *prima facie*, representative of the cometary

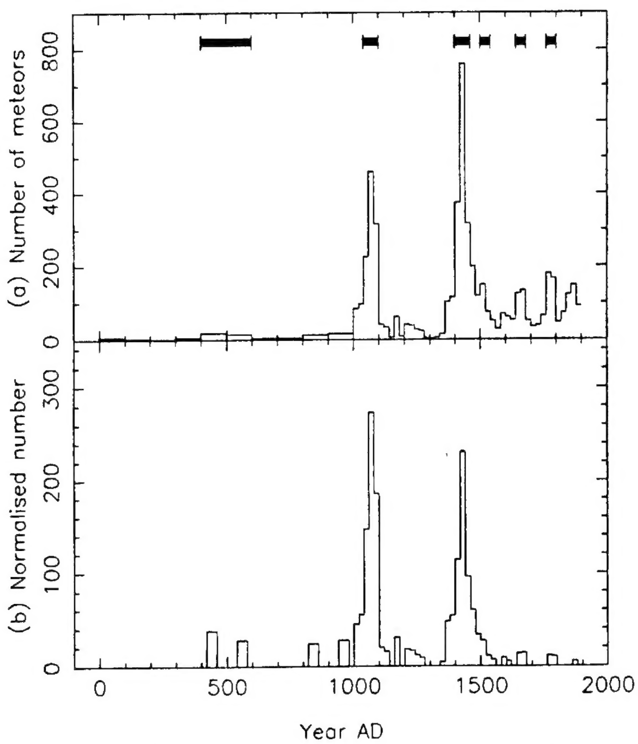

FIG. 1. (a) The recorded meteor flux in China over 19 centuries (Zhong *et al.* 1988) based on 100- and 20-yr counts before and after AD 1000 respectively (Hasegawa 1992). (b) The inferred 20-yr count over 19 centuries reduced and scaled in accordance with the (supposed) artificially increasing background flux, the latter being approximated by a centennial base of 15 and by centennial percentage increases of 0 (< AD 400), 7·4 (AD 400–1400) and 58·5 (AD 1400–1900), whilst also arbitrarily replacing the low fifth, sixth, ninth and tenth century enhancements by seemingly more realistic 40-yr peaks. Historically prominent increases in the meteor flux, not necessarily well calibrated, are marked with horizontal bars. These particular epochs are seemingly notable not only for their *a priori* portentous significance (see text) but for their social upheaval brought on by immediate millenarian concerns. The latter arise through a pre-scientific (presumably astrological) outlook, supposing a dominant cosmic influence on terrestrial affairs. In this paper, we isolate the Taurid progenitor as the likely 'cosmic influence'.

mass function generally, we note that the proposed evolution matches: (1) the increased resilience and fading through splitting as Oort cloud comets are transferred towards the Solar System; (2) the excess number of objects belonging to the supposedly derivative population of prograde comets in short period orbits close to the ecliptic which also contains large (cometary) asteroids, e.g. Chiron, Pholus; and (3) the large population of highly fragmented chondritic cores in the asteroidal belt necessary to explain the great bulk of primordial meteoritic material falling on the Earth, suggesting that similar pristine comets were present in abundance during the Solar System bombardment phase. Fundamentally then, the perspective we deal with here is one in which the solar nebula ceases to have a conspicuous role

and in which the formation of comets and proto-planets may precede the formation of stars.

Depending on the orbital/librational periods of the massive meteoroidal source and the effective mass spectra of the surviving debris dispersed through the ecliptic/resonance, we envisage a time-dependent erosion function which is multi-periodic and stochastic. The meteoroids generated (which may be jet accelerated) may then experience rapid comminution close to the Earth and Sun, thereby producing temporally correlated suspensions of dust in the terrestrial atmosphere and the inner Solar System environment. Such suspensions are the likely basis of underlying solar-terrestrial effects and we associate the more conspicuous (high velocity) erosion events with decadal-centennial enhancements of the meteoroidal flux at centennial-to-millennial intervals (Fig. 1). The latter are the subject of continuous historical record in China and intermittent millenarian concern (i.e. the perception of 'last times') in Europe, having frequently prompted serious social unrest. During the present century in particular, though increasingly during the last three centuries, it has been customary to regard such unrest and concern as sufficient in themselves to account for each other and any additional consequences, with the result that attention has been largely deflected from these high velocity erosion events and their specific astronomical cause. This is important so far as the period of close orbital intersection between the massive meteoroidal source and the Earth is concerned since it is the effects on mankind during these periods which are most likely to provide the primary justification for millenarian concern.

Here, we consider in turn how meteoroidal erosion events may affect the solar-terrestrial relationship (Section 2), a possible dynamical origin of the climate-proxy record (Section 3), the meteoroidal circulation and its likely source (Section 4), the latest era of close encounters between the Earth and the source (Section 5), the overall mass input to the Earth and its implications regarding the size of the source (Section 6), its relationship to the capture of giant comets in sub-Jovian space (Section 7), and the historical implications so far as the present hazard to civilization from space is concerned (Section 8).

2 SOLAR-TERRESTRIAL EFFECTS

Short term variations of solar structure, significantly longer than the internal thermal readjustment timescale of the photosphere and convection zone ($\sim 0{\cdot}1$ yr), are characterized by two well known magnetic cycles of $\sim$ 22 and $\sim$ 200 yr, the latter corresponding to the Wolf, Spörer and Maunder minima *c.* AD 1300, 1500 and 1700 respectively. The physical process driving these cycles, internal or external to the Sun, has not been identified though it seems to be agreed that changes in solar irradiance are in accordance with expected variations in the broad equatorial belt of toroidal magnetic field at the base of the convection zone (Gough 1990). Supposing that the photospheric adjustments which allow the observed modulation of the irradiance could ultimately be a consequence of reflected radiation due to dust insertions close to the ecliptic, it is interesting to consider whether a Solar System source undergoes erosion in accordance with the observed

cycles. In other words, we take as our basis a normally active state for the Sun (Weiss 1990), with magnetic field irregularities in the solar wind which give rise to locally reduced cosmic ray flux, and envisage a general solar-terrestrial relationship caused by the scattered sunlight from terrestrial and zodiacal dust accretions. We attribute such accretions to a periodically-cum-stochastically eroding source, simultaneously depressing terrestrial temperature and solar activity in accordance with the correlation between global cooling and isotope excess indicated by the climate-proxy record (Thomson 1990) and in accordance with the intrinsic planetary brightness record (Lockwood & Thompson 1991, Basu 1992).

Terrestrial and zodiacal dust accretions demonstrably depend on the inner Solar System meteoroidal flux. The flux reaching the Earth gives rise to both melted and unmelted components (e.g. Bigg & Thompson 1969), only the dust particles being too small to melt and burn up as meteors. An appreciable fraction of the meteoroidal input is made up of fragile large bodies ($1 \leqslant m \leqslant 10^6$ g) which disintegrate into swarms of dust particles above the atmosphere (Fechtig 1982, Ceplecha 1993). The meteor component (Hughes 1978), which is dominated by the so-called sporadic background of low velocity ($\leqslant 20$ km s^{-1}) meteoroids rather than by the generally high velocity meteoroids belonging to the more spectacular showers, is seasonally enhanced (Elford 1967). Specifically, the spatially flattened distribution of inner Solar System meteoroidal material, responsible for the zodiacal dust and for the sporadic background, is uniquely associated with a more coherent, comparable mass of such material in a broad, sub-Jovian, near-ecliptic stream aligned with the Taurids (see Dohnanyi 1978, Štohl 1984), which are likely therefore to provide the source. Enhancements of the sporadic and coherent components in the past appear to be simultaneous (see Fig. 3 of Hasegawa 1992), indicating a generally rapid dispersal of short lived meteoroids (Fig. 1) from the source, the ostensible erosion rate being $\leqslant$ 10 cm yr^{-1}. Through the Taurid association, both sporadic and coherent components of the meteoroid flux have an additional association with Comet P/Encke (Whipple 1967, Gustafson, Misconi & Rusk 1987) whose unexceptional size and appearance indicate two possibilities: a cometary source in common which is now largely dispersed or a substantial body in a superficially inactive state which is dynamically associated with Encke. That the latter alternative is possible is indicated by a conspicuously depleted component of the meteoroidal mass distribution requiring meteoric particles ($10^{-4} \leqslant m \leqslant 1$ g) discontinuously produced on timescales $\ll 10^4$ yr (Grün *et al.* 1985) which are extremely friable, whence it follows that the eroded source may be substantially devolatilized and inert.

In accordance with presumed wide variations in the cohesion of meteoroidal material arriving at the Earth, the constitution of which is based on a substantially unaltered chondritic-porous matrix, particles comprising the unmelted fraction of larger meteoroids reaching the Earth are essentially unobserved amongst the interplanetary dust particles collected from the stratosphere (Brownlee 1987). The implied further comminution in the atmosphere is consistent then with a discontinuous erosion in space which is generally associated with copious amounts of rapidly dispersed micron-submicron dust, as directly observed in the general vicinity of the orbit of

Comet P/Encke (Roosen, Berg & Farlow 1973, Singer & Stanley 1980). Thus we anticipate for inner Solar System meteoroidal material—essentially a chondritic-porous matrix variously impregnated with carbonaceous volatiles —a heterogeneously constituted source (cf. Whipple 1992) which may also be a large, currently sub-luminous body in close dynamical association with P/Encke. Such a body may well have been predominantly cometary in the past whilst being predominantly carbonaceous chondritic approaching chondritic (i.e. asteroidal) at present, implying a source that was large enough originally ($\geqslant$ 100 km say) to sustain internal differentiation through primordial and/or radioactive heating and fragile enough now to experience erosion events which produce a sensibly close match with the climate-proxy record.

It is plausibly supposed, on the basis of the inner Solar System fragmentation events now envisaged, that primordially processed cometary material which has experienced a high degree of devolatilization may be rather rapidly reduced to a continuum of particles in the size range $\sim 10^{-5}$–1 cm. Depending on the material's (low) dispersal velocity, such events may give rise to dust singularities or short-lived luminous sources due to scattered sunlight, possibly accompanied by tails and/or antitails, thereby contributing throughout history to a class of unattributed portents. In the longer term these sources will evolve into less conspicuous cometary trails. The nature of unattributed portents is not in general known of course, except through their negative attributes (non-stellar, non-cometary, non-eclipse etc.), but to the extent that the number recorded during the last millennium is comparable, say within an order of magnitude, to the number of cometary trails detected by *IRAS*, whilst the so-called Encke trail associated with Comet P/Encke is the most conspicuous object of its kind in the inner Solar System, it is reasonable to suppose the above cycles depend, via these fragmentation events, on the Taurid progenitor. Indeed, insofar as this particular trail is not symmetrically located with respect to P/Encke, there are observational grounds for believing the Taurid progenitor and this comet, though dynamically associated, may be distinct objects.

3 CELESTIAL DYNAMICAL PROCESSES

An orbital commensurability (resonance) with Jupiter can lead to a concentrated swarm of meteoroidal debris (see later) and a source librating within the resonance with the appropriate period ($\sim$ 400 yr) will encounter the swarm every $\sim$ 200 yr, providing a regular injection of new sub-Jovian dust. Similar encounters by the source or the swarm with a small particle concentration around Jupiter (Fechtig 1984) could be responsible for additional regular injections based on the orbital period of Jupiter, though since the small particle concentration around Jupiter will not be of indefinite extent, significant encounters of this kind may arise due to daughter objects of the source in more widely dispersed (Taurid) orbits rather than due simply to the source or the swarm itself. The frequencies of the interactions will depend on the number density and orbits of the objects involved, with an overall periodicity taking values close to the Jovian orbital period. The model predicts irregularities in these periods, and sunspot time series seem to

display appropriate instabilities in amplitude and frequency (Berger, Mélice & van der Mersch 1990). However, the individual daughter objects interacting in this way represent a comparatively small proportion of any dispersed membership, and are plausibly of lesser significance than the primary sub-luminous source. Since there is little or no prospect at present of establishing any precise characteristics for the relevant daughter objects, which have not been observed, our primary concern in the present paper is with the ~ 200-yr cycle and with the location and history of the primary source.

Fragile meteoroid and dust inputs to the inner Solar System influence the terrestrial environment both directly and, we suppose, indirectly through the Sun. As an indicator of past temperature, the growth pattern (tree-ring widths) of the Mount Campito bristlecone pine during the past $5\frac{1}{2}$ kyr (1 kyr = 1000 yr) is remarkable for the presence at high frequency of significant modulations (Thomson 1990), the most prominent of which is very close to twice the Jovian period whilst another is near $\frac{1}{7}$ this value (3·39 yr), possibly indicating a source object with orbital period $\frac{2}{7}$ that of Jupiter. Corresponding periodicities ~ 3·5 and ~ 10 yr, the latter correlating closely with the contemporary sunspot cycle, have been reported for the frequency of noctilucent clouds during the period 1920–1963 (Vasilev 1973), consistent with terrestrial and zodiacal dust accretion playing a fundamental role. Based on the ^{14}C content of cellulose in tree-rings, which is known to be correlated with longer-lived global climatic depressions during the previous well-studied thousand years (Wigley & Kelly 1990), the bristlecone pine record is also remarkable for the dominance at low frequency of modulations (the Suess wiggles) close to periodic values ~ 200 yr (Sonett & Finney 1990, Suess & Linick 1990, Thomson 1990). Since the atmospheric ^{14}C signature is very precisely matched by ^{10}Be which is aerosol borne (Raisbeck *et al.* 1990), and both signatures are significantly enhanced during the late Pleistocene glaciation, the correlated incidence (Sonett & Suess 1984, Oeschger & Beer 1990) during the present glacial-interglacial of Sun-modulated cosmic ray enhancements (responsible for the isotopic signatures on Earth) and climatic depression suggests a common explanation in terms of inner Solar System dust. This conclusion is likewise borne out by the 11- and 206-yr periodicities in thermoluminescence profiles of the last 18 centuries in sea-sediment cores (Castagnoli *et al.* 1990). In other words, we envisage a long-lived, initially prolific, cosmic dust source which librates in the 7:2 Jovian mean motion resonance and undergoes erosion as it encounters known concentrations of meteoroidal debris therein (see below), near Jupiter (see above) and near the Sun, in whose vicinity both the increased density of zodiacal dust and the higher temperature can be expected to have a significant effect. Such a librator experiences modest changes of phase and period at ~ 1 kyr intervals during random close passages to the Earth and Venus (see later) and appropriate modulations are present in the ^{14}C data (Neftel, Oeschger & Suess 1981, Thomson 1990).

The potential significance of these inferences resides in the expectation that a once very active comet, responsible for the late Pleistocene glaciation (Clube & Napier 1984, Hahn & Bailey 1990, Steel, Asher & Clube 1991), may now be dispersed into a conspicuously broad meteoroid stream with the

TABLE I
Taurid asteroids

	a	e	i	ϖ
Probable Taurids				
1991 GO	1·96	0·66	10	113
(4341) Poseidon	1·84	0·68	12	123
(4197) 1982 TA	2·30	0·77	12	129
1991 TB2	2·40	0·84	9	132
1984 KB	2·22	0·76	5	146
(4183) Cuno	1·98	0·64	7	170
(2201) Oljato	2·18	0·71	3	172
(5143) 1991 VL	1·83	0·77	9	177
1991 BA	2·24	0·68	2	189
Hephaistos group				
1991 AQ	2·16	0·77	3	222
(2212) Hephaistos	2·16	0·84	12	236
1990 TG1	2·48	0·69	9	238
1990 SM	2·16	0·78	12	243
(4486) Mithra	2·20	0·66	3	250
Stray object				
(2101) Adonis	1·87	0·76	1	32

All known asteroids selected on the basis of similarity in a, e and i (normalized to allow for its long-term variation) to a representative Taurid meteor orbit ($a = 2·1$ AU, $e = 0·82$, $i = 4°$, cf. Steel *et al.* 1991), but with no constraint on perihelion longitude ϖ. A reasonable range of ϖ to take as corresponding to the Taurid Complex, based on Taurid meteors, is $140 \pm 40°$. Assuming a uniform distribution in ϖ, the probability that eight out of 15 asteroids would have ϖ within that range is < 1 per cent. Furthermore, the alignment of 1991 AQ, (2212) Hephaistos, 1990 TG1, 1990 SM and (4486) Mithra appears quite remarkable so that these five asteroids could be e.g. the remnants of the previous giant comet or an early fragment of the present giant comet. Then the probability that of the remaining 10 asteroids, eight would by chance have ϖ within the range typical of Taurids is even smaller. Other methods also prove the existence of Taurid asteroids though precise details may differ, e.g. using q rather than a for selection suggests the interesting hypothesis that one or two small-a asteroids, like (1566) Icarus, could be Taurids. [N.B. 1991 BA is not a member of the population of km-sized objects, being one of the smallest asteroids ever observed at 5–10 m (Scotti, Rabinowitz & Marsden 1991). Asteroid 5025 P-L is also probably associated with the Taurids (Olsson-Steel 1987) though it is not included here, its orbit being unreliable.] See also Asher (1991), Steel (1992).

primary host close to an original orbit whose period and phase accord with the above specification. The primary host naturally includes a substantially asteroidal source (see above) comoving with many past meteoroidal fragments and it is to be expected that the most recent erosion event of any significance (say, within the last few hundred years) would generate a dust trail around the source, perhaps with a dynamically very similar comet inside or just outside the 7:2 Jovian resonance. Thus a meteoroid stream complex such as the Taurids possessing such features along with a significant number of near-Earth asteroids would clearly display vital signatures so far as any primary host of the proposed kind is concerned. No such host has been directly observed, so far as we are aware, but there are several indications that one nevertheless exists.

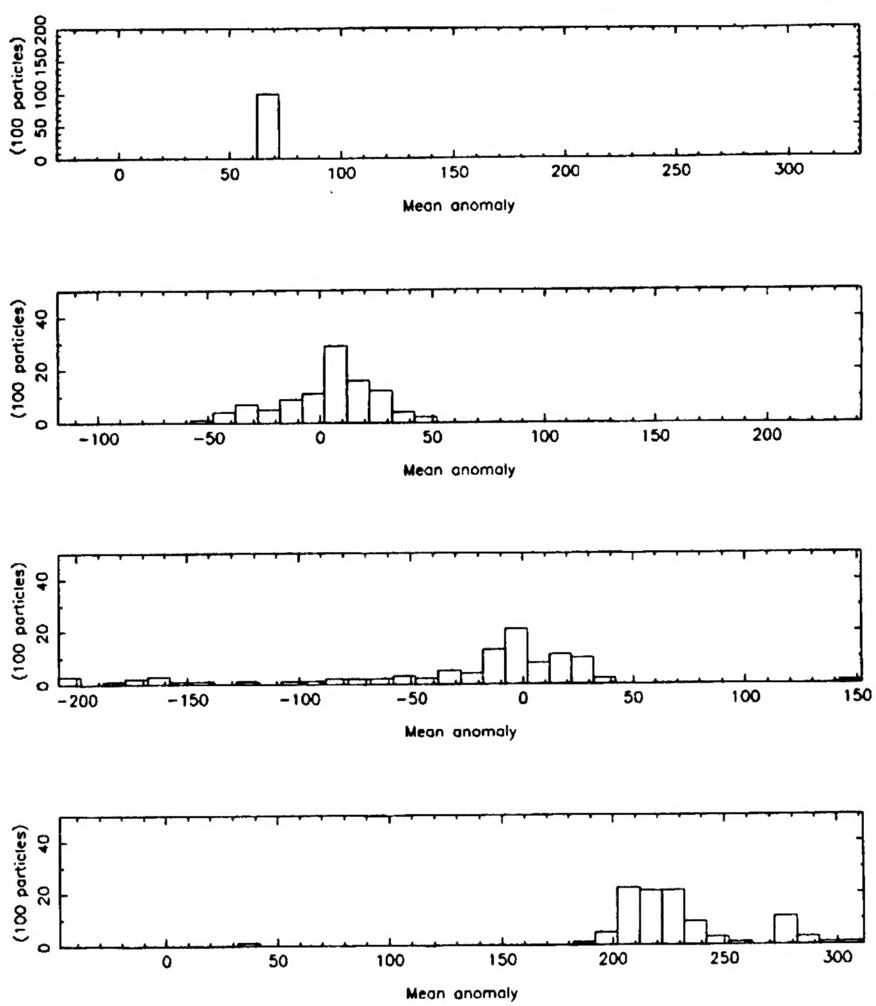

FIG. 2. Dust trail formed from the Taurid Complex progenitor after the presumed release of Comet P/Encke. The constraint that to be released from the resonant progenitor Encke must be in the resonant zone means that the event must have occurred between about 1772 and the Encke discovery date of 1786. Interestingly the previous favourable chance for Encke's discovery before 1786 would have been during the 1772 apparition (see Kronk 1984). Our computer models of the trail give better fits to the *IRAS* observations for starting dates nearer 1772. In the model shown here the particles separated from the parent in 1773 (first plot) with isotropic ejection velocities up to 15 m s^{-1} and the perturbative effects of Jupiter, Earth and Venus have been included. In each plot the mean anomaly M is positioned so that the resonance centre is at the centre of the plot. Thus initially the progenitor, Encke and dust particles are 80–90° behind the resonance centre and so at the back of the resonant zone. In the second and third plots (50 and 100 yr later) the motion forward though the resonance is shown. In the final plot M is shown at the time of the *IRAS* observations (mid-1983), when this model progenitor has $M = 215°$. The brightest part of the observed trail is between $M = 200$ and 260°. The resonant zone (at the centre of which we believe the meteoroidal swarm is concentrated) is between $M = 40$ and 220° so that the progenitor is near the front of the resonant zone, at the extreme of its oscillation.

TABLE II

Taurid swarm detections

Observation (+ reference)	Observation period	Swarm detection time	ΔM
Lightning-like phenomena on Moon (Giddings 1946)	1931 June 17	1931 June 17	7°
Dutch bright meteors (van Diggelen and de Jager 1955)	1947–early 1954	1951 Oct 28–Nov 11	35°
Lunar seismic experiment (Dorman *et al.* 1978)	1969–1977	1975 June 18–26	1°
Finnish bright meteors (*The Astronomer*)	1978 Nov 1, 1979 Nov 3	1978 Nov 1	23°
UV dayglow obscuration (Frank *et al.* 1987)	1981 Nov 1–1982 Jan 21	1981 Nov 1–10	−18°
Bright meteors (UK, Tenerife) (*The Astronomer*)	1988 Nov 2, 4	1988 Nov 2, 4	5°

Apparent detections of the presumed Taurid meteoroid swarm at the 7:2 Jovian mean motion resonance, based on various observational techniques. The 1981 November observation of short-lived obscuration patches in the terrestrial ultraviolet dayglow, understood as being caused by typical disintegrating meteoroids, is unacceptable unless such bodies are concentrated in space. Our model predicts a swarm encounter in 1971 (Table III) but the phase of the Moon was such that the seismic stations were badly placed. ΔM is the displacement in mean anomaly of the centre of the swarm from the Earth at the time of the Earth's passage through the swarm (see Fig. 3). Other resonances (3:1, 4:1, 10:3, 11:3) do not match all these timings. We note that the Tunguska meteoroid (Kresák 1978a) did not coincide with the swarm ($\Delta M \approx 84°$) and so is probably better understood as a single stray object in the Taurid Complex.

4 THE TAURID COMPLEX AND ITS SOURCE

Pre-discovery apparitions of P/Encke have not been identified (Whipple & Hamid 1972, Sekanina 1991) despite this comet having: (1) the shortest known period; (2) near naked eye visibility in 1786 (Kronk 1984, but see Kamél 1991); and (3) nodal intersections with the Earth's orbit in the past 2 kyr (Whipple 1940). Though absence of evidence does not necessarily imply evidence of absence, it is pertinent that the Taurid Complex (TC) is associated physically with Encke (Whipple & Hamid 1952, Steel *et al.* 1991) whilst also containing several Earth-crossing asteroids (Asher, Clube & Steel 1993; Table I), as proposed by Clube & Napier (1982, 1984). Thus it is conceivable that P/Encke is a reactivated cometary asteroid, in accordance with the existence of the conspicuous dust trail detected by *IRAS* close to the comet's orbit (Sykes, Hunten & Low 1986), indicating substantial particle emission within the last few 10^2 yr. However P/Encke is noted for its low dust content compared with other comets (Newburn & Spinrad 1985) and also is not located centrally within the trail (Sykes 1988). The orbital period of P/Encke ($P_E = 3{\cdot}30$ yr) relatively close to the 7:2 Jovian mean motion resonance ($P_R = 3{\cdot}39$ yr) may therefore be significant since the positions of P/Encke and the trail are consistent with the proposition that P/Encke split around 1786 from a substantially devolatilized TC progenitor (i.e. the asteroidal remnant of a once cometary source) which librates unseen within the resonance and has given rise to most of the dust constituting the trail (Fig. 2). The implicit ~200-yr age of the massive Encke trail is consistent

TABLE III

Swarm encounters predicted by model

Year (June)	ΔM	Year (Nov)	ΔM
1904	19	1900	18
1907	−22	1903	−24
1914	2	1910	0
1917	−40	1917	23
1921	25	1920	−18
1924	−16	1927	6
1931	7	1930	−36
1934	−34	1934	29
1938	31	1937	−12
1941	−10	1044	11
1948	13	1947	−30
1951	−28	1951	35
1955	37	1954	−6
1958	−5	1961	17
1965	19	1964	−24
1968	−22	1971	−1
1975	1	1978	23
1982	25	1981	−18
1985	−17	1988	5
1992	7	1991	−36
1995	−34	1995	29
1999	30	1998	−13
2002	−11	2005	11
2009	13	2008	−30

Meteoroids are concentrated within 60–70° in mean anomaly M with a gradual decrease over 10° or so at each end (Fig. 3). Encounters are listed here for M within 40° of the resonance centre. Calculations are based on the dates Nov 3 (pre-perihelion) and June 23 (post-perihelion).

also with the normal dust ejection velocity $\leqslant 4\ \mathrm{ms}^{-1}$ and avoids the anomalously high velocity $\sim 40\ \mathrm{ms}^{-1}$ suggested if the trail has a typical age ~ 20 yr (Sykes & Walker 1992).

A TC progenitor within the resonance for the last $\sim 10^4$ yr, though undetected, is evidently plausible given the apparent existence of a dense meteoroidal swarm centred on the resonance (Tables II & III, Fig. 3), indicating repeated meteoroidal emission in the past (cf. Steel *et al.* 1991). Such a progenitor would be present now either in the form of a single large object (Clube 1987) or, since repeated emissions (cometary splittings) are likely to include significant low velocity inputs, a host of smaller objects.

In contrast to the swarm, which is formed over many kyr by a resonant trapping mechanism and is distributed about the (dynamically defined) resonance centre, the trail, formed over a few centuries at most, has not had time to become greatly separated from the parent object, which at any one time (e.g. the present day) may be displaced substantially from the resonance centre. Therefore, the trail rather than the swam is the more direct clue to the libration period and current phase of the parent. The position of the trail close to the extreme of the resonant zone implies a high libration amplitude for the parent which in turn implies a high libration period ($P_L \approx 400$ yr; see Appendix A) so that the passages of the parent through the densest part of the swarm, when the parent will experience impacts from swarm meteoroids, occur every ~ 200 yr in accordance with the observed modulations of the

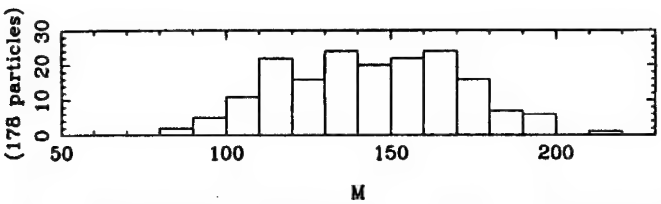

FIG. 3. Mean anomaly distribution of computer simulated swarm. Table II summarizes observations leading to the theory that at masses of 1–10^6 g, and probably higher, the TC is dominated by a meteoroidal swarm that has a crossing time of $\sim$ 10 days at the Earth and that is concentrated in just part of its orbit through the mechanism of the 7:2 resonance with Jupiter. At lower masses forces other than gravity will probably cause particles to be lost from the resonance over 10^4 yr. A swarm, as opposed to a stream uniformly spread round the orbit, is needed to explain why a concentration of meteoroids is observed in some years but not in others when it would have been detected had it been present. The detections and non-detections are plausibly explained if a parent object in the Taurid stream—in particular in the 7:2 Jovian resonance—has fed meteoroids into the resonance over the past 10^4 yr; the years of detection (as given by the M distribution—see Table III) and dates within years (as given by the cross-sectional distribution—see Asher 1991 for plots from computer models) are quite well fitted. Different models are possible depending on the nature of the parent's libration, e.g. a low amplitude librator ejecting particles at very low velocity would concentrate particles towards the resonance centre rather than immediately filling the resonance, but whatever the distribution at time of ejection, the effects (due to Earth and Venus) of spreading out from the resonance centre and being lost from the boundaries of the resonant zone cause an 'equilibrium distribution' to be reached over $\sim 10^4$ yr. A computer generated equilibrium distribution, derived from a combination of particles ejected near the resonance centre and to fill the resonance, is shown here. The value of M at the centre of the swarm (relative to which ΔM in Tables II and III are measured) is 142° (the timing is mid-1983 as for the trail simulation in Fig. 2; the slightly different M at the resonance centre is due to a small difference in ϖ).

terrestrial environment. The $\sim$ 200-yr periodicity in both climate and isotopic data is known to go back several kyr (Sonett & Suess 1984, Oeschger & Beer 1990), and the present configuration conceivably arose when the putative source drifted close to the resonance several (> 5) kyr ago, perhaps as a result of cometary outgassing, having since avoided any particularly close encounters with terrestrial planets. Though a $\sim$ 400-yr libration period is ordinarily short-lived ($\leqslant 1$ kyr) owing to perturbations by the Earth and Venus, planet-avoiding orbital evolutions of roughly the desired kind are occasionally found to occur (Fig. 4). It is possible that the present orbital configuration is maintained through circumstances whereby objects that have drifted into orbital commensurabilities are able also to avoid temporarily the general sea of planet-approaching orbits. The significance of the resonance could arguably extend to the progenitor's initial capture into the inner Solar System itself, i.e. the arrival of the putative source in sub-Jovian space up to 20 kyr ago consistent with the start of the late Pleistocene glaciation could in fact depend on a capture process which is most efficient for objects that drift (e.g. through various combinations of Jovian encounters) into orbital commensurabilities (cf. Milani *et al.* 1989).

Though a resonant meteoroid swarm could have arisen from a more stable librator of shorter period, with the present epoch corresponding fairly closely to the librator's earliest escape from the resonance after a significant perturbation, such an orbital history is not permitted by the climate/climate-

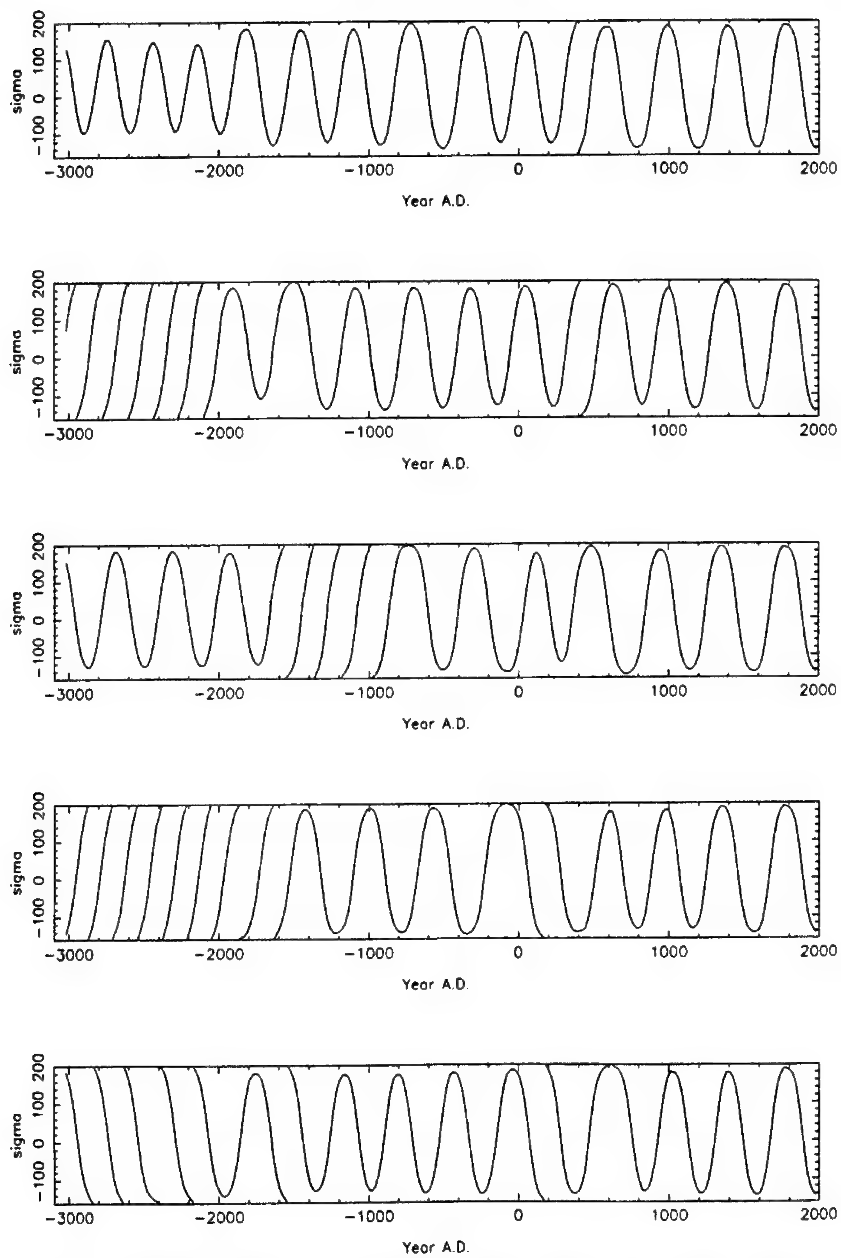

FIG. 4. Computer integrations of possible orbital evolution of Taurid Complex progenitor. The critical argument σ librates when the object is resonant. The effect of Jupiter, which causes the resonant librations, is included, as are those of the Earth and Venus, which cause perturbations of the libration. The orbital evolutions shown here display extended periods of time during which the libration period is around 400 years. The most likely times for perturbations of the libration can be seen to be 2000 BC and AD 500, periods of nodal intersection with the Earth and Venus (see Fig. 5).

proxy data. Moreover a scenario involving only weak perturbations so that the amplitude is continuously large also has the merit of avoiding any special distinction for the present epoch. These weak transitions tend nevertheless to occur during nodal intersections with the terrestrial planetary orbits, i.e. at epochs (year AD) $t_n \approx 500+2500n$; $n = \ldots -1, 0, 1 \ldots$ (see Table IV, Fig. 5, Appendix B). We cannot, of course, expect to resolve the issue of the long-term orbit in the present work, especially while the putative TC source has not been observed. Nevertheless, it seems that many observations coupled with these dynamical considerations do now allow a TC source which moves back and forth at or near the 7:2 resonance, encountering the swarm, so that the production of meteoroids and dust in the inner Solar System during the present glacial-interglacial ($\leqslant$ 20 kyr BP) is both periodic ($P_M = 0{\cdot}5P_L \approx$ 200 yr) and stochastic, depending on the encountered mass function of swarm members. Given the essentially chaotic nature of its orbit however, the predicted behaviour of the TC progenitor needs to be circumscribed carefully.

Ultimately the significance of this particular astronomical source resides in the current extraterrestrial input, which is dominated by sporadic meteoroids, a substantial proportion of which form a broad stream around the TC producing a greatly enhanced flux from the sunward and antisolar directions in April–June and October–December respectively (Štohl 1984). The $\leqslant 10^6$ g mass spectrum of disintegrating meteoroids reaching the Earth, supposedly undergoing electrostatic disruption during auroral plasma encounters (Fechtig 1982), is plausibly associated with this flux as well as with the meteoroidal swarm, given that: (1) probable TC meteors and dust due to meteoroid disintegration have been directly observed (Bigg & Thompson 1969); (2) disintegrations due to swarm members are plausibly inferred from simultaneous lunar (Dorman *et al.* 1978) and terrestrial (Kaufmann *et al.* 1989) encounters in 1975; (3) micro-submicron dust resulting from the erosion and fragmentation of swarm members appears to be directly observed in space (Roosen *et al.* 1973, Singer & Stanley 1980); and (4) the disintegration products of most meteoroids reaching the Earth apparently experience further comminution in the atmosphere in accordance with direct observations in space [N.B. most stratospheric interplanetary dust particles are evidently exposed to radiation in space (Bradley, Brownlee & Fraundorf 1984, Brownlee 1987), consistent with their prior existence as zodiacal dust]. Therefore, we envisage a heterogeneous but fragile TC progenitor that is responsible for the still barely detected complex of similarly fragile yet massive meteoroids in sub-Jovian space, and whose encounters with the heliocentric, Jovian and swarm environments are a continuing source of Solar System meteoroids and dust, producing modulations of the extra-terrestrial input at $\sim 3{\cdot}39$, $\sim 23{\cdot}7$ and ~ 200 yr periods respectively. Indeed, where it was once supposed that a rainfall-aerosol-meteoroid connection might best be explored through its association with the more spectacular meteor showers (Bowen 1953, 1956, Whipple & Hawkins 1956, Kviv 1987), an exploration based on periodicities associated with the likely resonance of the putative TC progenitor now seems appropriate.

TABLE IV

Precession rates for 7:2 resonant Taurids

Amplitude in M	Libration period (yr)	Time (kyr) for one cycle of ω
85°	400	4·5
70°	330	5
50°	270	6·5
30°	250	8·5
10°	250	10

The libration period and precession rate will be expected to drift over timescales of several kyr owing to the effect of the Earth and Venus in perturbing the orbit to librations of different amplitude. Epochs of nodal intersection lasting a few centuries occur twice per cycle of argument of perihelion ω. The libration period of interest to us is 400 yr though this will drift and in the text we adopt an interval between epochs of nodal intersection of 2500 yr, corresponding to a period of revolution of ω of 5000 yr.

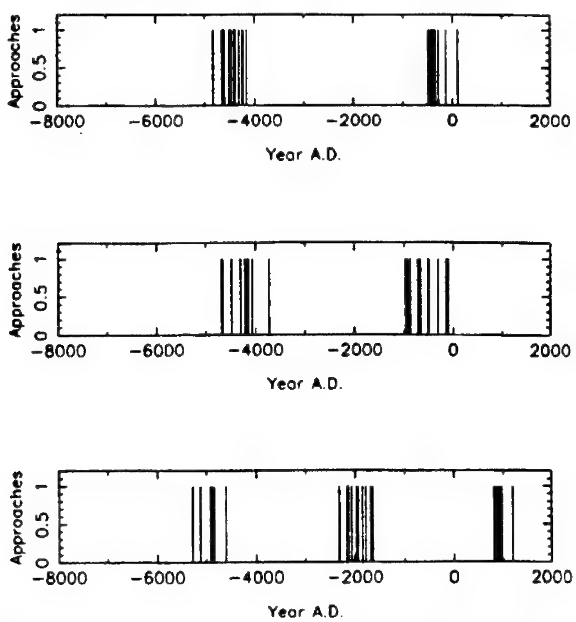

FIG. 5. Times of approach to within 0·05 AU of the Earth or Venus (not shown separately; it turns out that for orbits of the kind we are studying the epochs of nodal intersection, spanning a few centuries and spaced for a few kyr, are similar for both planets) for three 7:2 resonant Taurids. The third particle has the fastest precession rate (cf. Table IV) so that the epochs are spaced by about 3 rather than 4 kyr.

5 THE TERRESTRIAL RESPONSE

The $\sim$ 200 yr modulation of the bristlecone pine $\Delta^{14}C$/climate-proxy (global cooling) data has its phase (peak $\sim$ AD 1900) in accordance with the position of the *IRAS* trail and 20th century global warming, whilst the intermittent global cooling generally (e.g. *c.* AD 1300, 1500, 1700) is consistent with meteoroid flux enhancements induced by the TC progenitor during

resonant swarm passages. Furthermore, the meteoroid flux enhancements are in the direction expected for a more generally reduced meteoroid production during the Holocene, following enhanced cosmogenic nuclide production during the late Pleistocene glaciation (Oeschger & Beer 1990) when the disruption index of the progenitor is likely to have been at its initial maximum value (Oort 1950; see later). This would indicate that TC meteoroid flux enhancements, whilst controlling the flow of dust into the terrestrial atmosphere, not only maintained the conditions of enhanced and reduced optical depth under which the late Pleistocene glaciation and subsequent Holocene interglacial were produced (and modulated), but also independently influenced the Sun in such a way as to affect the incoming cosmic ray flux to the Earth and hence the production in the terrestrial atmosphere of various radiogenic species (^{14}C, ^{10}Be, etc.). The external modulation of the Sun is of course an important consequence of the celestial dynamical process (see above) with implications for the solar and Maunder cycles which are not further considered here. Rather we note the approximately decadal dust-veil events on Earth, which appear to be unrelated to the Δ^{14}C record and which are commonly attributed to the global effects of extreme volcanic eruptions (Baillie 1990), since these also allow the possibility of exceptional meteoroidal encounters with the Earth—i.e. super- and multi-Tunguska events—which are not necessarily directly correlated with the underlying meteoroid generation process. Thus we note that exceptional overproduction of meteoroids and dust may arise in the TC, due to rare encounters by the progenitor with bodies at the top end of the meteoroid mass function or cometary splittings induced in some other way. This effect appears to be demonstrated by the random distribution in time of seven major Δ^{14}C enhancements during the Holocene, of which three during the last 1500 yr are otherwise regarded as 'astonishing' (Oeschger & Beer 1990).

In addition to these many factors indicating a probably close physical relationship between our TC model (specifically the progenitor) and the terrestrial record, as evidenced so far as the latter is concerned in tree cellulose by its growth pattern and cosmogenic signature, it is particularly noteworthy that low frequency signatures of the bristlecone pine's growth accord very well with the progenitor's expected orbital transitions. Thus its two most persistent orbital states apparently occur respectively outwith and within the interval ~ 2700 BC–AD 500 (dates derived by inspection of Figure 5 of Thomson 1990), though in the latter case to a reduced extent from ~ 1800–1100 BC. At least two of these dates (~ 1800 BC, ~ AD 500) correspond rather closely with epochs of nodal intersection by terrestrial planetary orbits ($n = -1, 0$ respectively). Therefore, we believe that the underlying celestial dynamical process and the terrestrial evidence relating to the Holocene are essentially compatible and that the seven epochs since 3000 BC registering greatly enhanced ^{14}C and ^{10}Be are now plausibly associated with massive progenitor fragmentations, corresponding latterly to at least one observed increase in the Taurid meteoroid flux (Fig. 1). It follows that the most recent enhancements of the TC flux lie within a post 5th century increase in ^{14}C and ^{10}Be, coinciding initially with the progenitor's latest nodal intersections at 1 AU as well as with the inferred fragmentation epoch of a significant Taurid

source distinct from though in a similar orbit to P/Encke (Whipple & Hamid 1952). Thus it is conceivable that the increase relates to an extreme or final breakup of the progenitor during a near-Earth or near-Venus passage around this time and that we should attach particular significance to these recent epochs *c.* AD 400 and 600 as marking a period of possibly exceptional bombardment of the Earth. More generally however, we consider the possibility of a substantial cometary progenitor at the heart of the TC which has been reduced during the latter part of the Holocene to the state of an asteroidal/meteoroidal cluster.

6 MASS INFLUX TO EARTH

Though variations in the atmospheric isotopic content expressed as time series allow the effects of the meteoroidal input to the Earth to be demonstrated, an estimation of the mass influx is easier from astronomical rather than terrestrial environmental considerations. We are picturing the following structure in the TC. The parent (whether a dominant single object or gravitationally bound cluster of small extinct cometary bodies) is presumed to move on a librating resonant orbit and meteoroids ejected with low enough velocity ($\leqslant 50$ m s^{-1}) remain in the resonance (i.e. become part of the resonant swarm) whilst those ejected at higher velocity enter the Taurid stream as a whole, i.e. extending considerably beyond the 7:2 resonance. Dynamical modelling (Whipple 1940, Whipple & Hamid 1952, Babadzhanov, Obrubov & Makhmudov 1990, Steel *et al.* 1991) has yielded timescales $\sim 10^4$ yr for the present orbital element dispersion in the Taurid stream. More dispersed still is the broad sporadic stream surrounding the Taurids, associated perhaps with a timescale of $\sim 2 \times 10^4$ yr.

From visual and radar observations of meteors, the mass of the TC is 1–2×10^{17} g (Asher 1991) between meteoroid masses of 10^{-6} and 10^6 g, based on a mass function that falls off at high masses (Štohl 1987). However, this mass function does not predict km-sized asteroids ($\sim 10^{15}$ g) and so is hardly representative for the system as a whole. Thus the TC is known to extend to considerably larger objects, the orbits of sporadic fireballs being similar to Taurid orbits (Dohnanyi 1978) and a statistically very significant number of asteroids being aligned with the complex (Table I). Including high-mass objects is likely to increase the total mass of the complex by at least an order of magnitude: compared to the number of asteroids listed in Table I, most of which are in the diameter range 0·5–2 km, we may expect ~ 10 times as many Apollo asteroids to exist at the upper end of this range, with discoveries at 0·5 km perhaps only 1–2 per cent complete (Steel 1992). At masses of $\sim 10^{11}$ g the complex is represented by the Tunguska object of June 1908 (Kresák 1978a). From the lunar cratering record, one object of this size impacts Earth every ~ 300 yr (Shoemaker 1983) and the timescale for single objects on Taurid orbits to hit Earth is 10^{8-9} yr (Öpik 1976, Steel & Baggaley 1985) so that if a significant proportion of smaller craters is due to impacts by the disintegration products of giant comets (and we note the important contribution of the TC to the terrestrial influx observed at all masses) this yields 10^6 such objects in the complex. Indeed this figure derived from the long-term cratering record may well be increased (~ 10–100 times) on account of the past several millennia being an era of particularly high

bombardment, during the physical disintegration of the giant comet. We note in passing that this does *not* imply Tunguska objects every few years; rather it implies multiple bombardments at centennial to myriannual intervals (Clube & Napier 1982, 1990, and see later).

These considerations suggest values for M_{TC} ($m \leqslant 10^{11}$) $\sim 10^{18}$ g and M_{TC} ($m \leqslant 10^{18}$) $\sim 10^{19}$ g, the former corresponding to an annual terrestrial influx $\dot{m}_{TC} \sim 10^{11}$ g yr^{-1}, possibly accounting for most of the total annual influx to the Earth (e.g. Hughes 1992). This figure is indeed up to two orders of magnitude greater than the underlying background flux $\sim 10^9$ g yr^{-1} based on measurements of the Ir and Os content of deep sea sediments (Barker & Anders 1968) and trace elements on the lunar surface (Anders *et al.* 1973), and comparable to the repeated spasmodic increases during terrestrial history reaching $\geqslant 10^{11}$ g yr^{-1} for periods $\leqslant 10^5$ yr. The present epoch is demonstrably unexceptional in the long term therefore, provided we envisage a history of repeated domination by disintegrating giant comets at average intervals $\sim 10^6$ yr. The repeated domination does not itself have to be regular and it is possible to envisage temporary intervals as short as $\sim 10^5$ yr, as at present, provided the periods of extended domination ($\sim 10^7$–10^8 yr) are interspersed with quiet spells of similar duration corresponding to a virtual absence of comets (Clube 1987). To the extent however that the present interaction between the Earth and the mass influx of meteoroids is catastrophic, resulting in airbursts and impact explosions due to bodies $\leqslant$ and $\geqslant 1$ km respectively, we emphasize: (1) that the present is representative of a uniformitarian process in Earth history; and (2) that the swarm and its source are not only characteristic of the most severe celestial hazard throughout terrestrial history, but are currently 'active' on a millennial to myriannual timescale.

To set these estimates of M_{TC} and $\dot{m}_{TC}$ in perspective, we note that the swarm mass limited to the observed range of meteoroids (1–10^6 g) is probably several 10^{17} g (Asher 1991) implying that the TC is concentrated in the swarm. The conclusion could well extend to higher masses in which case the swarm and its source themselves dominate the annual influx to the inner Solar System, in accordance with the view that the zodiacal complex as a whole probably derives from a single large object. Many authors have of course anticipated this conclusion since the present population of ordinary short-period comets is hopelessly inadequate to maintain the current zodiacal cloud (Whipple 1967, Delsemme 1976, Kresák 1980). Thus, over the past $\sim 2 \times 10^4$ yr, the disintegrating Taurid progenitor has probably supplied the particles in the mass range 10^{-4}–1 g required by Grün *et al.*'s (1985) collisional model of the zodiacal complex; the required mass input is 10^{14-15} g yr^{-1}, equivalent to the total disintegration of one Biela-like dead comet every few 10^2 yr, supposing the Taurid progenitor is a swarm of such objects. The giant comet supplies the Taurid/sporadic stream, from which meteoroids undergoing collisional evolution (Olsson-Steel 1986), with the resultant smaller particles suffering circularization of their orbits by the Poynting–Robertson effect, feed the background zodiacal cloud. As already indicated, the bulk of the material released during these disintegrations is likely to be dispersed through and from the inner Solar System fairly rapidly and may, supposing the TC meteoroid observed to produce meteors (Bigg & Thompson 1969) is typical, be some 10^2 times more massive than that

entering the zodiacal cloud. This ratio would imply a current mass for the Taurid progenitor, assuming the losses during the last 10^3 yr do not exceed a few per cent, of $\sim 10^{19}$ g and an original mass, based on the zodiacal cloud mass in particles $\leqslant 1$ g (Whipple 1967), of $\sim 2{\cdot}5 \times 10^{21}$ g. These figures bear out the fundamental hypothesis that we are dealing with a once very large comet (radius ~ 100 km) which has now degenerated into a virtually defunct cometary asteroid (radius ~ 10–20 km say) accompanied by a family of substantial meteoroids.

7 GIANT COMETS AND COMETARY ORIGINS

The flux of large objects near the Earth is dominated ($\geqslant 90\%$) by Earth-crossing asteroids rather than active comets (Kresák 1978b, Shoemaker 1983, Bailey 1991). Although chaotic regions of the asteroid belt can supply a number of near-Earth asteroids of the right order (Wetherill 1988), the best estimate from these theories is still only about half of the population estimated from observations. It may be that most Amor asteroids (those that have perihelion just beyond Earth's aphelion) come from the asteroid belt whilst a substantial proportion of the asteroids that cross the Earth's orbit (and are therefore important as regards the Earth impactor population), which typically have higher eccentricities, are dead comets. Hartmann, Tholen & Cruikshank (1987) found that asteroids identified on orbital grounds only as probable dead comets tend to have spectral properties more similar to those of comets. Assuming in general that comets are constituted heterogeneously, it is to be expected that a significant number of short-period comets evolve both physically, to become asteroidal in appearance, and dynamically, to become decoupled from Jupiter, thereby turning into typical Apollo asteroid orbits (Wetherill 1991). It is highly likely, then, that the question of the Earth impactor flux is closely connected with the origin of Jupiter family comets.

Everhart (1972) studied whether the roughly isotropic long-period comet population from the Oort cloud could give rise, primarily through Jovian perturbations, to the predominantly low-inclination Jupiter family and found that low-i, pro-grade orbits are captured preferentially, with the period distribution also reproduced well. Quinn, Tremaine & Duncan (1990) showed that although the capture probability is indeed an order of magnitude greater for low-i ($0° \leqslant i < 9°$) than isotropic orbits, these low i-values occupy so little isotropic phase space than even this increased capture probability is not sufficient to reproduce the flattened Jupiter family distribution. However, among comets captured within 1000 perihelion passages (reasonably supposing that the comets become inactive after $\leqslant 10^5$ yr), they found that 25 per cent of the captured Jupiter family have i-values of less than the observed median (10°). Some discrepancy remains, but if many Jupiter family comets represent the splitting products from one very large short-period comet (dynamical lifetime $\sim 10^5$ yr: Hahn & Bailey 1990) then the low-i distribution is quite acceptable. Indeed, if the flattened system extending beyond Neptune is itself substantial due to enhancements of the isotropic flux in the not-so-distant past, then the splitting of a giant comet in an orbit of comparatively low i-value seems to be a natural and reasonably

characteristic way to explain the observed distribution of Jupiter family comets.

Cometary splitting, which has often been observed to occur (Pittich 1972), also helps to explain the inadequacy by possibly two orders of magnitude (Fernández & Ip 1984) of the observed number of Oort cloud comets to provide the short-period population as a whole. Thus it is not necessary in principle to invoke the existence of hypothetical unseen reservoirs such as the Kuiper belt (Duncan, Quinn & Tremaine 1988) or a dense inner core of the Oort cloud (Stagg & Bailey 1989) to account for short-period comets. However, since the short-period comets, which are large enough to have asteroidal cores, (and which are not trapped in sub-Jovian orbits) may have physical lifetimes in excess of their dynamical lifetimes, the short-period comet population may well include at least one evolved (i.e. asteroidal) giant comet. The observation of the cometary asteroid 2060 Chiron, therefore, may well reinforce the presumption of cometary splitting and points to the observed (classical) Oort cloud as the primary source of short-period comets. Indeed the orbital energy distribution of the classical Oort cloud is very sharply peaked at near parabolic values and it is known that planetary perturbations tend to flatten this peak in an equilibrium distribution. A disruption index that diminishes as comets age is thus implied (Oort 1950), in accordance with an observed tendency amongst newer comets to split and disappear during perihelion passage (Whipple 1992) and a corresponding tendency amongst survivors to more gradual fading due to the presence of more asteroidal, presumed daughter products of occasional larger comets. It follows that we expect the flux of near-Earth objects to be dominated by the capture into the inner Solar System of the largest comets and that these disintegrate to produce a large number of smaller (active) comets and (inactive) asteroids. The population of near-Earth objects is thus populated discontinuously by occasional very large comets from the Oort cloud, the circumstances relating to the release of asteroids/meteoroids during the evolution of the TC being typical. The importance in this context of dynamical complexes or streams of minor Solar System bodies is now increasingly recognized (Obrubov 1991, Steel 1991).

To sum up, the top heavy mass function of observed long-period comets (Donnison 1986) provides basic support for the fundamental role of giant comets. The direct observation of cometary splitting coupled with an evolving disruption index amongst long-period comets points to a dominant role for giant comets which are differentiated and heterogeneously constituted. We anticipate that the disintegration products of the asteroidal cores of giant comets will therefore dominate the ecliptic environment. The observation of possible remaining cores of several large comets (944 Hidalgo, 2060 Chiron and 5145 Pholus) apparently confirms the general importance of these objects. Indeed, the relative frequency of the evolved giant comet phenomenon coupled with the comparative stability of the Taurid swarm and its resonant source could be significant for general reasons relating to the capture of short-period comets since the arrival of a substantial cometary source on a dynamical timescale an order of magnitude greater than its random period of survival (Nakamura & Yoshikawa 1991) appears to favour orbital commensurabilities, including resonances, which avoid close planetary approaches. Extensive orbital integrations of the known planet-

crossers in sub-Jovian space have already indicated that objects of the so-called Oljato class (Milani *et al.* 1989), with orbits very similar to the Taurids, are the most likely intermediary state for escapes that will join the cometary system beyond Jupiter. However, though the Taurid configuration is therefore a dynamically permissible end-state for new entries, its probability is not yet secure. Notwithstanding the uncertain nature of some of these considerations, this new perspective on the evolution of small Solar System bodies, embracing the Oort cloud through to the population of near-Earth objects, typified by the currently dominant meteoroidal system (TC) and its variable mass input to the Earth, raises important questions regarding the present and future hazard to civilization, which are commonly overlooked (e.g. Morrison, 1992; cf. Clube 1992).

8 CELESTIAL HAZARD TO CIVILIZATION

Chinese records of the terrestrial meteor flux over the last 19 centuries (Zhong *et al.* 1988) indicate seasonal maxima (Hasegawa 1992) and associated radiants (Astapovič & Terenteva 1968) consistent with a variable Taurid source which is frequently dominant. Although the absolute calibration of these records is uncertain due to unknown variations in the monitoring process and detection threshhold, they suggest a quasi-stochastic Taurid source function with likely flux enhancements (Fig. 1) around (AD) 400–600, 1040–1100, 1400–1460, 1500–1540, 1640–1680 and 1760–1800, the latter bracketing the supposed formation epoch of the current Encke trail. We note that a clear distinction may be drawn between variations since the 18th century and prior to this period, as the former very strongly reflect increasing scientific activity whilst the latter reflect a fairly uniform, slowly extending, observational regime. During this regime Oriental astronomical interests, like those in Europe, lay with portentous rather than astrophysical phenomena, the maintenance of suitable records being to a large extent professionally organized in China only (Schafer 1977). Given the presumed portentous nature of the observational material, whatever the astrophysical reality behind the recorded meteor flux and its correlates, we can be reasonably sure that the phenomena, especially during the periods of their dominance, would most probably have been understood in China *and* Europe as exemplars of a natural (presumed astrological) process in which the cosmos necessarily interfered with terrestrial affairs. The enhancements of the meteor flux are thus of particular interest in their European context as the periods of their incidence also happen to coincide with periods of pronounced social and intellectual upheaval when the normal ascendancy of secular over fundamentalist views of the cosmos experienced a sharp reverse, these views in turn being characterized respectively by a supposed non-interference and interference in terrestrial affairs by cosmic agencies. We note, for example, corresponding with the above epochs: the dark age foundation of the Holy Roman Empire, the initiation of the crusades against Islam, the great schism, the reformation, the English revolution and the French revolution. On each occasion, the revived fundamentalism in Europe (which lasted a century or more at first) became increasingly short-lived but characterized always by a renewed intense interest in demonic agencies, especially their destructive tendencies, perceived as a millenarian threat

(Cohn 1957). The prevailing tendency nonetheless, since the 12th century, increasingly has been to regard demonic agencies as a heresy (Thomas 1971), leaving open the question therefore of their possible eschatological associations at earlier epochs.

Speculations of this kind relating to P/Encke and the Taurids are not new. Thus the idea that P/Encke, due to the precession of its orbital nodes, would have been responsible for specially impressive meteor showers around the time of Christ was advanced originally more than 50 years ago (Whipple 1940, also the reply to Clube 1987). The connection between this epoch and the passage of the perceived Taurid source clearly indicates an early appreciation of the comet's possible eschatological associations based on its presumed substantial size and its presumed domination of sub-Jovian space during recent millennia. The prediction did not however lead to any revealing historical insights and therefore was set aside. The present enquiry on the other hand, whilst appealing to similar principles, evidently draws attention to another, possibly more relevant, set of facts. Thus the observations no longer lead us to focus on the historical implications of P/Encke (it did not exist!) but on those of a larger configuration, the Taurid host, which, on account of its presumed meteoroidal content, subject to random replenishment, evidently has very serious eschatological implications (i.e. possible multi- and super-Tunguska bombardment) for epochs *c.* AD 400 and 600.

The origin of the Tunguska missile is not known but its relatively close association with the TC, based on its date and radiant (Kresák 1978a, but see Sekanina 1983), indicates as much a relatively close association with a disintegrating giant comet as with the longer-lived population of near-Earth asteroids, corresponding therefore to a current average for the Tunguska flux in the range $\sim 0{\cdot}01$–$1\ \mathrm{yr}^{-1}$ (cf. Shoemaker 1983, Clube & Napier 1986, 1990). The upper end of this range would indicate an overall input $\sim 10^3$ objects in the size range $0{\cdot}1$–1 km during periods of nodal intersection (i.e. every few millennia) and raises the question whether the epochs *c.* AD 400 and 600, corresponding to the periods in Europe when the empires centred on Rome and Byzantium came under the severest pressure, also mark a general reverse in civilization due to extended bombardment by the Taurid host around this time. We have noted already that the period leading up to the collapse of Rome coincides with the onset of millenarianism in an extreme form (Barb 1963) along with a growing conviction that near-Earth space is populated with unfriendly 'demons' (Cohn 1976). Moreover both Byzantium and Rome were to emerge from the reverse with an altogether greater concern for the consequences of divine interference in terrestrial affairs. In fact, the so-called 'dark-age' is characterized in Europe by the seemingly random deterioration and desertion of substantial tracts of land coupled with the migration of peoples on a quite massive scale (Esmonde Cleary 1989). The predicted Tunguska flux, supposing in fact that a disintegrating giant comet is involved, suggests an area the size of Britain would experience at least one such event during the reverse, thus providing a not implausible interpretation of the British catastrophe *c.* AD 440 recorded by Gildas (e.g. see Myres 1986) which preceded an early significant migration to northern France (Morris 1973). The secularization of history has of course proceeded for many years hand-in-hand with the rejection of catastrophe and astronomical signs. The

question can surely now be raised whether this process has gone seriously astray.

The belief in demons, as imperatives of our understanding of the environment, was not in fact erased until the 17th century, prior to the enlightenment. Furthermore, it has been customary ever since this time to suppose the near-Earth environment is not particularly hazardous. It seems now however that the various signatures of a still unseen source of the Taurids may have placed us in touch with a once accepted version of the historical process during the last five millennia which has carried very little weight these last 300 years. We note for example that the 'dark age' reverse corresponds to the epoch of Proclus and Augustine, both of whom envisaged a host of demons, or fallen angels, which originated in the past from a primary celestial source, a fact which it has been said (Taylor *c.* 1800: see references in Temple 1976) is the recognized crux of most ancient knowledge. Proclus headed the neo-Platonist school in Athens and evidently subscribed to Plato's description of catastrophe recurring at long intervals due to a swarm of invisible bodies (e.g. Appendix I in Temple 1976). The crucial facts underpinning this knowledge are of course even more ancient, and consistent with the assumption that fragmentation events during an earlier, more visible phase of the evolution of the Taurid progenitor were widely observed.

Given our model, it seems appropriate to note the presolstitial observations recorded in China and Rome of a supposedly common source with a following trail in 76 BC and before AD 79 (Bicknell 1987) which may be associated with the expected relatively close passages by a prominent Taurid meteoroidal aggregate at these times. Specific records of this kind at these times raise the possibility of course of more general sightings and it is an interesting question therefore whether the curious contemporary references in Greek and Roman literature to the red Sirius are also relevant. Thus the latter's fearful historical attributes, ascribed also to the Sun on a supposedly seasonal basis, namely a 'bronze' mouth and a 'flashing' mane (Ceragioli 1992), would seem to have an equally plausibly association with contemporary presolstitial observations relating to our putative cometary source. This explanation likewise would imply much of the astrophysical speculation concerning the red Sirius at this epoch is spurious, resulting from displacements of the name of an ancient cometary source (during its final decline) to either of the two brightest stars.

Turning to more recent times, given our model, it also seems appropriate to mention the interesting study by Bronshten (1973) tending to associate the Tunguska fall with frequent June–July sightings of noctilucent clouds in the 20- to 30-yr period beginning $\sim$ 1880. While it is generally supposed nowadays that noctilucent clouds were only discovered in 1885, Bronshten also refers to solitary significant observations in 1648 and 1781–1783, corresponding apparently to the Taurid flux enhancements discussed here.

9 FINAL COMMENTS

The reader will recognize that this paper draws together many facts of astronomical, terrestrial and historical knowledge, all dependent, it seems, on the existence and evolution of a single celestial body. The body however has not been observed in modern times, and while various aspects of the

TABLE V

Proposed orbital elements of source object

	a	e	i	Ω	ϖ	M
	2·256 AU	0·847	11·9°	334·2°	160·2°	215°
Uncertainty	0·01 AU	0·03	0·2°	0·5°	1°	5°

The values e, i, Ω, ϖ are simply those of Comet Encke, with the uncertainties imposed by the requirement of matching the IRAS pictures. The values a and M are constrained by the computer modelling of the trail (see Fig. 2). M is at year 1983·48 (the time of the *IRAS* observation).

present story may well be argued in different terms, reducing the emphasis on large differentiated comets—e.g. the Tunguska flux is fundamentally uniform (Shoemaker 1983); the Encke trail is entirely derived from Comet Encke itself (Sykes *et al.* 1986); asteroidal/meteoroidal complexes such as the Taurids (Table I, and see also Obrubov 1991) are illusory (Wetherill, private communication)—it seems to us that the combined evidence for a recent large comet does have an overall coherence (the helion/antihelion circulation in sub-Jovian space does after all exist!) and that the single most important fact providing the putative astronomical source and its terrestrial effects with credibility would now be its detection. We hope therefore that observers will take an interest in searching for the source (see Table V), noting also the rather serious implications (periodic global warming, sudden global cooling, occasional bombardment) for civilization if it exists.

Though we have discussed at length the occurrence and importance of the events generating meteoroids and dust in the inner Solar System, it is the epochs of nodal intersection with the Earth of the parent object, on similar orbits to which many objects in the TC can still be expected to be moving, that signify the most dramatic increases in the influx to Earth. This represents a previously unexplored possibility arising from currently available data and the next epoch (comprising a pair—pre- and post-perihelion—of intersections and spanning a few centuries) is predicted around AD 3000 (i.e. $n = 1$), increasingly close passages by the putative source being expected well in advance of this epoch.

It should nevertheless be noted that the resonant swarm theory (Fig. 3, Table III) can be constructed just from the observations (Table II) which are hypothesized as being due to this swarm. This theory thus stands independently of the inferences made in this paper about the exact nature of the resonant libration of the parent object.

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APPENDIX A: RESONANT OSCILLATIONS

In this work we are interested in the long-term (timescales of millennia) precession of angular elements, since the argument of perihelion ω determines when the Earth's orbit is intersected (see e.g. Steel *et al.* 1991), with consequent terrestrial interaction with meteoroids, and in the shorter-

term (timescales of centuries) behaviour of particles that librate in a resonance. Most of this paper's dynamical results are derived from orbital integrations but in these appendices we include some analytical formulae for illustrative purposes.

Turning first to resonant librations, we allow for perturbations from Jupiter only in the first instance and simplify the problem so that the short-term variations in a and anomaly are considered for fixed values of e, i, Ω and ω (and Jupiter assumed moving on a fixed ellipse). Neglecting very high frequency fluctuations we obtain the analytical expression

$$-\frac{1}{4}\sqrt{\left(\frac{Gm}{a_R}\right)}\dot{a} = h_1 \sin\phi - 2h_2 \sin 2\phi \qquad \text{(A 1)}$$

as a good approximation for motion in the 7:2 resonance. Also

$$\dot{\phi} = 3\sqrt{(Gm)}\, a_R^{-5/2}(a-a_R) \qquad \text{(A 2)}$$

where m is the mass of the Sun, a_R is the semi-major axis (2·256 AU) corresponding to the resonant period and $\phi = 7\lambda_J - 2\lambda$ (+ an additive constant so that the centre of the oscillation in ϕ is 0), λ_J and λ being the mean longitudes of Jupiter and resonant particle respectively. The derivation, including expressions for the coefficients h_i (which are functions of a_R, e, i, Ω, ω and Jupiter's elements), has been given by Asher (1991) but is omitted here because (Fig. A 1) although the analytical theory (including the numerical values of the h_i) describes the smoothed motion of the particle very well, the high frequency fluctuations in practice make it necessary for integrations to be done. Theory and integrations do however provide encouraging confirmation of each other while the above equations enable us to illustrate the motion qualitatively. They give a correct quantitative description also if we regard a as a smoothed rather than instantaneous value (the two may differ by up to $\sim$ 0·005 AU, compared with oscillations of up to $\sim$ 0·025 AU about a_R).

Apart from a and ϕ, all quantities in the equations are (or are being approximated as) constant so that we have a straightforward description of the combined behaviour of (a, ϕ), with the initial (a, ϕ) determining the subsequent motion. We shall see shortly that a is interesting in relation to energy considerations; ϕ is interesting since it directly shows the longitude behaviour. The 'resonance centre' moves at exactly 7/2 the angular speed of Jupiter and ϕ gives the oscillations of a resonant particle's longitude about the resonance centre. For the 7:2 case there are two resonant zones, each extending $\pm 90°$ about the resonance centre so that $\pm 90°$ in λ is the largest possible libration amplitude. Thus each resonant zone also moves at $\frac{7}{2}\dot{\lambda}_J$. We presume the Taurid parent and meteoroid swarm to be in just one of the zones as apparently observed. Particles in the resonance undergo small oscillations in a about a_R and simultaneous oscillations (1/4 cycle out of phase) in ϕ. Thus $\dot{\phi} > 0$ (i.e. $\dot{\lambda} - \frac{7}{2}\dot{\lambda}_J < 0$) when $a > a_R$, as expected since while the period is above P_R, the particle drifts backward through the resonance zone, and conversely. For Taurids in the 7:2 resonance it turns out that h_2 is of order 10 per cent of h_1 and that the hs are negligible from h_3 onwards (e.g. in units of AU and yr and with $GM = 4\pi^2$, $h_1 = 0{\cdot}000403$ and $h_2 = 0{\cdot}000038$ for $e = 0{\cdot}85$, $i = 12°$, $\Omega = 334°$, $\omega = 186°$; h_i values for other typical 7:2 Taurid elements are similar), so that (h_i being positive) $\dot{a} < 0$ whenever $0 < \phi < 180°$, i.e. when the particle is behind the resonance centre, and conversely.

Physically the resonant motion is dependent on the high e (see e.g. Section 12 of Greenberg 1977) so that there is a part of the orbit (aphelion) during which Jupiter's orbit is most closely approached and during which Jovian perturbations are therefore concentrated. Jovian forces act so as to avoid conjunction with Jupiter happening at the time of aphelion passage. The initial (a, ϕ) determines whether 'reflection' back into the resonant zone (see Öpik 1976) takes place before conjunction at aphelion ever has the change to occur. If 'breakthrough' (Öpik 1976) out of the resonant zone takes place then the particle is near, but not actually in, the resonance, and ϕ circulates rather than librates. The librations of largest amplitude correspond to particles least strongly trapped in the resonance, since only small perturbations are needed to displace particles out of the resonant zone.

The additive constant in ϕ is mainly -5ϖ (ϖ = longitude of perihelion), to allow for the fact that time of aphelion passage is what controls resonant behaviour, but there is a further small adjustment to allow for the difference between Jupiter's true and mean longitudes at the longitude of the particle's aphelion, since it is true longitude that determines whether conjunction occurs. The 'critical argument' σ is usually defined as $\sigma = 7\lambda_J - 2\lambda - 5\varpi$ (e.g. Yoshikawa 1989).

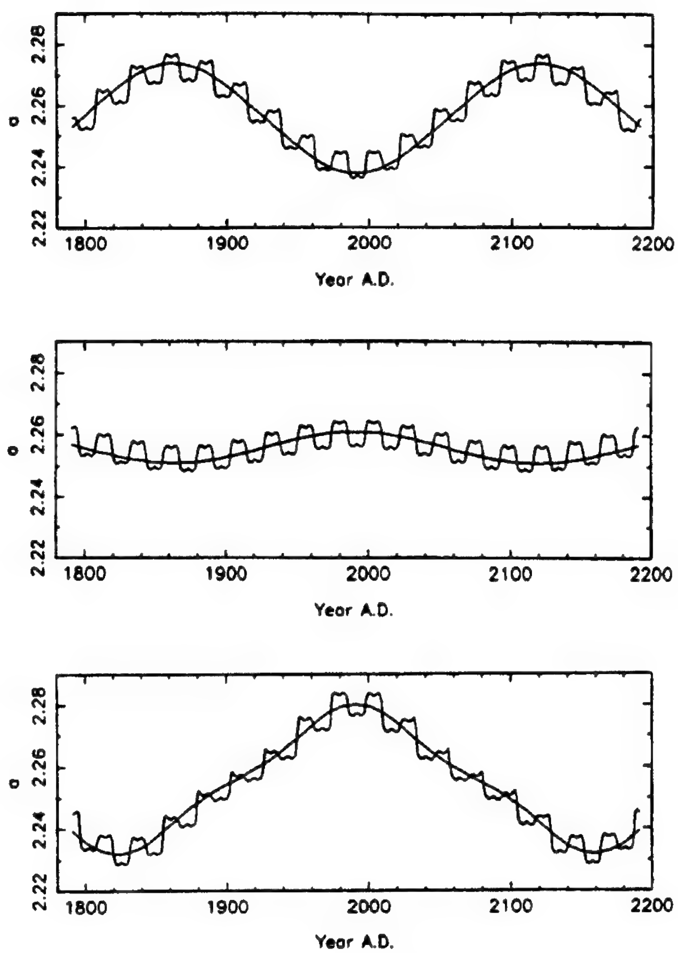

FIG. A1. Orbital behaviour of three 7:2 resonant Taurids (with different libration amplitudes) as given by smoothed analytic theory and by numerical integration.

Any initial (a, ϕ) determines period, amplitude and phase. The period and amplitude of the oscillation described by the two equations are easily calculated on a computer. Most initial pairs of values lead to a libration period P_L in the range $\sim$ 250–350 yr (in good agreement with integration results), though $P_L \approx 400$ yr can occur. This period corresponds to a high amplitude ($> 160°$ in ϕ) so that λ librates by more than $\pm 80°$ about the resonance centre. This period-amplitude pair of values together with its phase are evidently important so far as the Encke trail model is concerned.

Jupiter, then, controls the resonant motion we are considering in this paper. However, the orbits cross those of the terrestrial planets and it turns out that on timescales of kyr, energy changes induced by passages near the Earth and Venus (best thought of as occurring randomly, though with greater frequency during epochs of nodal intersection) cause effectively instantaneous changes in a (energy is proportional to $1/a$) that we cannot ignore. Thus there is an instantaneous transition from a resonant oscillation of one amplitude and period, to another (or even from a resonant to non-resonant orbit). We have to be concerned therefore with the stability of P_L. Either by performing large sets of numerical integrations, or by using

TABLE AI

Secular precession rates

	$e = 0{\cdot}7$		$e = 0{\cdot}8$		$e = 0{\cdot}9$	
a	ω	ϖ	ω	ϖ	ω	ϖ
1·5	29500	117900	26600	136900	23900	183200
1·6	25400	103000	22700	119100	20200	158400
1·7	21900	90200	19400	103600	17100	136900
1·8	18800	79000	16500	90100	14300	118000
1·9	16200	69100	14000	78200	11900	101400
2·0	13800	60400	11700	67600	9800	86500
2·1	11700	52600	9800	58200	7900	73100
2·2	9900	45600	8000	49600	6200	60900
2·3	8200	39200	6400	41700	4700	49700
2·4	6700	33400	5000	34500	3400	39200
2·5	5300	28000	3700	27800	2200	29200

Secular periods in (yr) of revolution of ω and ϖ for different values of a and e. The Taurid Complex is probably not old enough (perhaps < 20000 yr) for any of these orbits to have precessed all the way round the sky in longitude.

the theory to tabulate libration amplitudes and periods corresponding to different (a, ϕ) values, it is found that a given energy perturbation has a proportionately much greater effect on a libration of period ~ 400 yr than on those in the range ~ 250–350 yr so that, relatively, the 400-yr period is less stable. Nevertheless the period can occasionally survive, within ± 10 per cent say, for a few kyr (Fig. 4).

APPENDIX B: ANGULAR ELEMENT PRECESSION

To obtain similarly useful analytical insights into the long-term evolution of Taurid orbits, we may describe this evolution in terms of simple formulae whose applicability has also been checked with respect to full scale orbital integrations. The long-term precession of Taurids was calculated by Whipple (1940) from consideration of Jovian perturbations during aphelion passages of the Taurid particle. Brouwer (1947) derived formulae for the secular perturbations of the orbital elements due to Jupiter (the dominant influence). These conveniently show the pattern of the angular element variations (previously demonstrated by Whipple) as well as allowing the calculation (simple on a modern computer) of overall long-term precession rates. In this theory Jupiter is assumed to be on a circular orbit and we require the particle's orbit to lie entirely inside that of Jupiter. The method is then to limit the disturbing function to secular terms only and if we follow Brouwer's working, the following expressions provide a very good description of the secular motion (provided that i is low enough compared to e, which holds for Taurids):

$$\begin{aligned} a &= \text{constant} \\ \omega &= \tan^{-1}(R \tan St) \\ \varpi &= \varpi_0 + Kt \\ i &= 2\tan^{-1}\sqrt{(\gamma/[A - B\cos 2\omega])} \\ e &= \sqrt{(1 - (H/[\cos i])^2)} \end{aligned} \qquad \text{(A 3)}$$

with $\varpi_0, \gamma, H, A, B, R, S$ and K constant for any single particle—ϖ_0, γ and H are chosen to fit initial values and A, B, R, S and K are functions of a, e and (weakly) i (details in Asher 1991). As an example, for Comet Encke we have (units of degrees and yr) $A = 2{\cdot}43$, $B = 2{\cdot}12$, $R = 0{\cdot}263$, $S = 0{\cdot}053$, $K = 0{\cdot}0068$.

For low-e orbits R is nearer 1, so that the rate of change of ω is more nearly uniform but with Taurids ω precesses much more rapidly through 90 and 270° than through 0 and 180°. Also any Taurid orbit has i varying by a factor of a few, with maximum values of i when ω is at 90 or 270° and minimum values at 0 and 180°. Therefore ω (also Ω) varies most quickly when i is lowest. Finally, with Taurids the time for one revolution in ω is several times less (as opposed to half in the low-e case, cf. Sykes & Greenberg 1986) than for one revolution in ϖ. Though the secular theory operates in the frame of Jupiter, it is acceptable in this discussion to neglect the difference between the orbital planes of Jupiter and Earth.

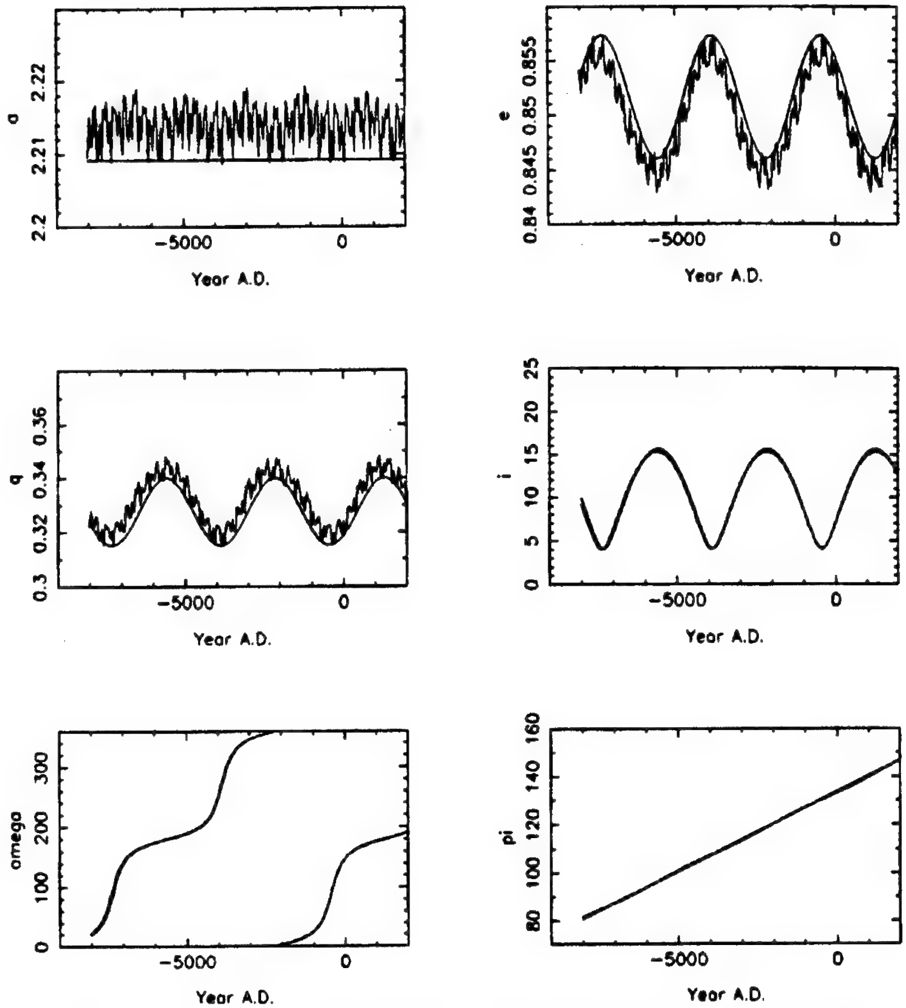

FIG. A2. Evolution of orbital elements; comparison between secular perturbation theory and numerical integrations. The present-day elements of Comet Encke are followed back in time allowing only for the perturbations of Jupiter, considered in a circular orbit. Angular elements are plotted relative to Jupiter.

In this paper we are particularly interested in the behaviour of ω, since this determines the epochs of intersection with the Earth's orbit. A typical example for a Taurid orbit would be ω = 65, 115, 245 or 295° resulting in nodal intersection. Each pair of values will be separated by no more than a few centuries, with successive pairs spaced by half the period of revolution of ω.

A comparison with full scale orbital integrations indicates that the secular theory does not reproduce the small, high frequency variations in a, e, q but the longer term changes in these elements are predicted almost perfectly (Fig. A2), except in the region of strong Jovian resonances, as expected since certain periodic terms in the disturbing function, neglected by the secular theory, no longer average to zero. The 7:2 resonance turns out to be quite strong.

Table A1 shows precession rates derived from this theory. Jupiter's non-zero eccentricity affects these secular rates by amounts up to ~ 10 per cent, allowed for successfully in Whipple's

(1940) calculations of the orbital evolution of Encke's Comet by virtue of using genuine measurements of observed perturbations in Encke's elements. Jupiter's non-zero e also produces a secular effect in e (equivalently perihelion distance), important for example in Steel *et al.*'s (1991) work on Taurid meteors but which need not concern us here.

For 7:2 resonant orbits it turns out that the *pattern* of angular element variations is almost exactly as given by the secular theory but that the *rate* changes. Orbits with the lowest libration amplitudes (and periods) are those that best avoid Jupiter when they go through aphelion so that the effect of Jovian perturbations may be expected to be less. This is confirmed by integrations. Table IV, which we presented earlier, showed angular precession rates for various orbits in the 7:2 resonance, as measured by how far back in time one has to go to reach the appropriate ω-values for nodal intersection. The phase of the resonant libration has little effect on the rates since over a whole libration period, Jupiter has the same total effect on orbits with the same libration amplitude, whatever the phase.

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